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SESSION 5

ANTARCTIC SEA ICE VARIABILITY AND CHANGE: PHYSICAL LINKS WITH THE SOUTHERN OCEAN

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ABSTRACTS SUBMITTED TO THE (CANCELLED) SCAR 2020 OSC IN HOBART

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Modeling new ice formation under the influence of ocean waves

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In sea ice modeling the focus has been on the basin to climate scale processes. New ice formation has received less attention. Field observations in the Southern Ocean consistently reported the ubiquity of pancake ice in the marginal ice zone. The presence of this type of ice has also become prevalent in the Arctic Ocean during the fall-winter season. Field observations have also shown that new ice is very effective in damping high frequency ocean waves. Such findings have motivated more refined sea ice models. In this paper, we briefly review the mathematical framework for the new ice formation in sea ice. We then propose an algorithm to expand existing sea ice models to include new ice types in the presence of waves.

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Spatio-temporal variations in snow properties on sea ice in the Weddell Sea, Antarctica

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Snow on sea ice alters the properties of the underlying ice cover as well as associated exchange processes at the interfaces between atmosphere, sea ice, and ocean. As Antarctic snow cover persists during most of the year, it contributes significantly to the sea-ice mass and energy budgets due to comprehensive physical (seasonal) transition processes within the snowpack. However, field studies reveal not only a strong seasonality but also spatial variations from local to regional scales. It is therefore necessary to quantify seasonal snow processes, such as internal snowmelt, snow metamorphism, and snow-ice formation at multiple spatial scales on Antarctic sea ice.

Doing so, we present here a compilation of in-situ observations of physical snow properties on different spatial scales revealed during expeditions in the Weddell Sea since the early 2000s, covering spring, summer, autumn, and winter conditions.

Results from snow pit analyses in the Weddell Sea during both austral winter and spring reveal a high spatiotemporal variability of snow parameters highlighting the need to distinguish between seasonal and perennial snow regimes. Also, the origin of the sampled ice floes and the respective atmospheric conditions experienced must be considered for distinguishing different snow regimes in the Weddell Sea.

Combining data of vertical snow structures from spatially and temporally local measurements (point measurements) with snow accumulation data from ice-tethered autonomous platform (buoys) drifting through the Weddell Sea year-round (trajectory data) allows to investigate seasonal snow processes for the entire Weddell Sea basin.

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Sea-ice growth from the top: Meteoric ice and snow in the northwestern Weddell Sea, Antarctica

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Summer sea ice extent in the Weddell Sea has increased overall during the last four decades, with large interannual variations. However, the underlying causes and the related ice and snow properties are still poorly known.
Here, we present results of the interdisciplinary Weddell Sea Ice (WedIce) project carried out in the northwestern Weddell Sea on board the German icebreaker R/V Polarstern in February and March 2019, i.e. at the end of the summer ablation period, focusing on 21 ice cores sampled for texture, salinity and isotope analysis.
The ice at the coring sites had an average thickness of 178 cm with an average snow depth of 13 cm and a consistently positive freeboard. Isotope and salinity analyses revealed an average meteoric ice fraction of 23%. This included about 17% (22cm) snow-ice, saline sea ice formed by flooding and refreezing of snow at the snow/ice interface. In contrast, superimposed ice, fresh sea ice formed through melting and refreezing of snow only, account for about 6% (11cm) of the sea-ice thickness. Within the study region between 62°S and 66°S, no spatial gradients were apparent. However, this study reveals a higher proportion of superimposed ice compared to previous campaigns in both the same and other areas of the Weddell Sea, indicating changes in the amount of surface summer melt/thaw.
These results highlight the importance of a better understanding of snow accumulation and metamorphism patterns on Antarctic sea ice as it might be a major component controlling the evolution of the underlying sea-ice cover.

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Seasonality of sea-ice and snow properties from autonomous ice-tethered platforms in the Weddell Sea, Antarctica

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Studying seasonally varying snow and sea-ice properties in the ice-covered oceans is a key element for investigations of processes between atmosphere, sea ice, and ocean. A dominant characteristic of Antarctic sea ice is the year-round snow cover, which substantially impacts the sea-ice energy and mass budgets, e.g. by preventing surface melt in summer, and by amplifying sea-ice growth through extensive snow-ice formation. However, substantial observational gaps in the seasonal cycle of the Antarctic pack ice and its snow cover lead to a limited understanding of important processes in the ice-covered Southern Ocean. Here, we introduce a unique observational dataset comprised of a number of critical parameters relevant to sea ice and its snow cover, recorded by a suite of snow and ice-mass balance buoys (IMBs) deployed in the Weddell Sea between 2013 and 2019.
Using snow buoy data, we infer a year-round, mainly event-driven snow accumulation of up to 90cm on the Weddell Sea pack ice, which only melts during the summer months after drifting into the marginal ice zone. Vertical temperature profiles from co-deployed IMBs are used to validate these findings, and to calculate energy budgets across the atmosphere-ocean boundary. From these calculations, we get highest monthly sea-ice growth rates of about 10cm in May, while sea-ice melt is most dominant in the marginal ice zone with a monthly rate of about 50cm in December.
Our results highlight that data from autonomous, ice-based platforms are a key element in better understanding sea-ice and snow properties and their seasonal evolution.

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Climate Response to Projected Antarctic Sea Ice Loss

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Since accurate satellite records began, Antarctic sea ice cover has slightly increased, but with significant regional variation. Antarctic sea ice is projected to dramatically decrease by the end of the 21st century if greenhouse gas concentrations continue to rise. Sea ice plays a significant role in climate of the high latitudes of the Southern Hemisphere, whereby changes may have resultant consequences on the large-scale atmospheric circulation, such as the Southern Annular Mode. Other impacts may include changes to the Meridional Overturning Circulation and consequently, further afield climates. Despite this, limited studies have been conducted on the impacts of Antarctic sea ice loss. Using the UK Met Office HadGEM3 model, we have run a coupled model explicitly simulating the climate response to Antarctic sea ice loss via an albedo feedback mechanism. Results indicate a 'mini global warming' response to Antarctic sea ice loss alone. The Southern Hemisphere dynamic response leads to a negative SAM index associated with an equatorward shift in the westerly jet, agreeing with previous studies. However, results are not only confined to the Southern Hemisphere, but reach as far as the Arctic, causing subsequent Arctic sea ice loss. To determine the atmospheric and ocean pathways, we have also run an atmospheric only model. Here we will propose a mechanism for this cross-hemispheric process and accentuate the importance of using a coupled model.

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Fast ice controls on turbulent mixing rates on the West Antarctic Peninsula shelf

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The ocean surface boundary layer (OSBL) experiences momentum and buoyancy input from the atmosphere, which are strongly implicated in the seasonal development of the mixed layer. However, in polar shelf seas during winter, the presence of a rigid layer of fast ice can render a profoundly different OSBL, where fluxes are strongly suppressed. While the under-ice OSBL has been extensively studied in the Arctic, no study, to the best of our knowledge, has quantified the dissipation rate at the same location under contrasting fast-ice covered and fast-ice free conditions in the Antarctic. In this study, we report on a set of hydrographic and turbulence observations taken in February and August 2016 in Ryder Bay, West Antarctica, alongside accompanying meteorological and velocity observations. The results yield a profoundly different OSBL in the two seasons. Dissipation rates in the top 100 m are strongly enhanced in the ice-free season compared with the fast-ice covered season (values of ~6 x 10-9 W kg-1 compared with ~1.5 x 10-9 W kg-1). Analysis of a neighbouring moored ADCP suggests that this is attributable to a significant increase in wind-generated near-inertial energy in the upper ocean during summer. By contrast, in winter, dissipation in the top 30 m of the water column appears to exhibit a law-of-the -wall type scaling. While the upwards heat fluxes are modest (typically 1.5 W m-2), the rapid reduction in West Antarctic fast ice observed over the last 30 years may lead to a change in the dynamics of the OSBL.

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Summertime winds, seasonal heat storage, and wintertime ice in the southern ocean

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Stronger summertime westerly winds lead to anomalously cold sea surface temperature in the following weeks and months. Here we present a mechanism by which these winds can also cause anomalously warm wintertime sea surface temperatures and a reduction in the maximum wintertime sea ice extent. Strong summertime winds lead to enhanced vertical mixing, which draws heat downwards from the warmer surface waters. At the same time, anomalous atmospheric heat fluxes act to damp the cold sea surface temperature anomalies, drawing additional heat into the ocean. As the mixed layer deepens during the autumn months, the subsurface heat anomalies are brought back to the surface, leading to anomalously warm sea surface temperatures and reduced sea ice extents. Using a combination of observations and models we assess this mechanism in a zonally averaged context, and speculate about its importance regionally.

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The asymmetric seasonal cycle of Antarctic Sea Ice in the CESM Large Ensemble

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Each year, Antarctic sea ice takes seven months to grow to its maximum extent but only five months to melt. Wind-driven Ekman transport has been suggested as a key mechanism driving this asymmetry with the direction of the Ekman transport depending on the position of the ice edge in relation to the circumpolar trough that circles the continent between 60° and 70°S. During autumn, easterly winds act to slow the advancing ice edge, whereas in summer, Ekman divergence, created by opposing winds on either side of the low-pressure band, opens up warm water regions that rapidly melt sea ice. However, this mechanism has so far not been quantified.

We examine the relationship between asymmetry in the annual cycle of sea ice extent and the position and intensity of the circumpolar trough in the 40 ensemble members from the CESM-LENS historical run (1920-2005). CESM-LENS reproduces the annual cycle of sea ice extent well and these outputs are a useful tool for investigating the variability of the annual cycle. We find the greatest variability in melt rates, whereas growth rates remain consistent. We show that deepening of the circumpolar trough leads to increased melts rates, thereby supporting the role of divergence in increasing the rate at which Antarctic sea ice melts. The role of winds versus the stabilizing effect of the ocean during the growing season remains unquantified.

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An idealized model to simulate different scenarios of ocean, atmosphere and sea-ice interactions

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The interaction between atmosphere, ocean, and ice plays a significant role in global sea-level rise, an essential area of climate change research. The growth and melt of Antarctic sea-ice occur as a result of ocean-atmosphere exchanges of heat, momentum, and freshwater as the combination of the ocean and atmosphere circulation. However, the sea-ice cover variations are not a passive phenomenon but a variety of positive and negative feedback effects among those three components. Exploring the sea-ice dynamics and ocean-atmosphere interaction is crucial to understanding the Antarctic climate system and, therefore, the global climate system. Ocean-ice modeling highlights the sea-ice biases as a significant contributor to the uncertainties in future predictions over Antarctica, ice sheet mass balance, and sea-level rise. We developed a controlled idealized domain over the Southern Ocean, aiming to identify the interaction of the different processes driving the sea-ice melt and growth annual cycling. Our ocean-ice numerical model was developed using Regional Ocean System (ROMS) with Budgell sea-ice thermodynamics and consists of a generic ocean with topographic and ocean features common to the Southern Ocean forced by atmospheric climatological fields (pressure and temperature) and completely geostrophic winds. The model evolution can prognostically calculate ice concentration and thickness and produce a feedback response that changes the ocean-air exchange of heat. Based on that, several scenarios were created to identify mechanisms through which the sea-ice dynamics are affected (and affect) by the ocean and the atmosphere.

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Antarctic Sea Ice Extent Reconstructions during the 20th Century

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Antarctic sea ice plays an important role in climate variations across the continent, as well as globally through connections in the ocean. Yet, little is known about the range of Antarctic sea ice extent variability prior to the modern satellite era of 1979. Indeed, the dramatic rapid decrease of Antarctic sea ice in 2016 after decades of increase demonstrates that the Antarctic sea ice system has marked variability that we do not fully understand.

This presentation will evaluate preliminary reconstructions of Antarctic sea ice extent based on a linear statistical model, principal component regression. Two sets of reconstructions will be analyzed, including a monthly reconstruction that employs Antarctic station data as a predictors as well as midlatitude data, but only extends back to 1957, and seasonal reconstructions based primarily on midlatitude predictor data that extend back to 1905. The skill of these reconstructions will be demonstrated through independent validation techniques, and the range of historical sea ice variability, including the recent change, will be evaluated on much longer timescales. Such work helps to increase the understanding of Antarctic sea ice variability and change and has implications for research in Antarctic atmospheric science, the Antarctic cryosphere, the climate modeling community, as well as the Southern Ocean.

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The influence of mixed layer dynamics and ice-ocean feedbacks on the seasonal cycle of Southern Ocean Sea ice

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The seasonal cycle of the sea ice extent in the Southern Ocean is strongly asymmetric with a relatively slow increase followed by a more rapid decrease after the winter maximum. This asymmetry is strongly conditioned by the changes in winds and more generally by the atmospheric forcing. Nevertheless, the evolution of the mixed layer depth and of the ocean-sea ice heat flux is also very different between the growing and retreat seasons, with generally higher upward heat fluxes in fall when the mixed layer is thickening. Furthermore, the evolution of the mixed layer is not independent of that of the sea ice, as the surface layer dynamics are controlled by the brine released during ice formation. This role of ocean surface dynamics and ice-ocean interactions in the seasonal cycle of the ice extent is investigated here using several simulations obtained with a new eddy-permitting (1/4°) NEMO-LIM Southern Ocean configuration including ice-shelf-cavities. Specifically, the mixed layer depths and ice-ocean feedback are frozen in sensitivity experiments to quantify the contributions of the various processes.

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Antarctic Sea-Ice Decadal Variability since 1980

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It has been nearly four decades since Sea-ice extent (SIE) satellite data started being stored and studied. I will present a new approach for the SIE statistical distribution to examine decadal changes as a function of season for each regional sea around Antarctica using Probability Density Function (PDF).
The presentation follows an article, written by me and other researchers, sent to submission on the Journal of Geophysical Research this January 2020, exploring the SIE data from National Snow and Ice Data Center (NSIDC). Where the results show a significant decadal difference in the SIE normal PDF between both the Weddell Sea sector (48% of differing data distribution between 1982-1993 and 2006-2017) and the Amundsen-Bellingshausen (55%) for Austral Summer. These two Sea sectors is where most of the Southern Ocean SIE variability occurs (Weddell representing 61% from the SIE growth and Amundsen-Bellinghausen the only sector presenting a SIE decrease). In Spring the largest contribution to SIE growth is seen in the Ross Sea (43% differing data from 82-93 to 06-17). The largest decadal differences in data distribution from 82-93 to 06-17 of the Southern Ocean is observed in Austral winter, where all individual Sea sectors present a SIE growth.

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Wave modulation of the Antarctic marginal ice zone extent

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The Marginal Ice Zone (MIZ) is the highly dynamic outer belt of partially ice-covered ocean formed by unconsolidated or broken ice where ocean waves, atmosphere, and sea ice processes are closely interlinked. This belt is operationally defined as the region where sea ice concentration falls between 15 and 80 percent. Like consolidated sea ice, also the MIZ plays a pivotal role in the global climate system by altering fluxes of energy, mass, and momentum between the ocean and atmosphere as well as modifying the ocean surface albedo. Knowledge of the extent of the MIZ and processes modulating it are fundamental for climate predictions. Long term satellite data records provide an extensive database for the investigation of the MIZ and its extension and variability. Here we will discuss the correlation between ocean surface waves and the extent of MIZ. To accomplish this task a database of sea ice concentration from the Ocean and Sea Ice Satellite Application Facility (OSI-SAF) and Advanced Microwave Scanning Radiometer (AMSR-2) as well as altimeter observations of significant wave height and wind speed obtained from the Australian Ocean Data Network (AODN) will be used. Both data-sets cover a period of 34 years spanning from 1985 to 2019. Results indicate that the MIZ extent is modulated by wave height with large extents occurring in months of energetic wave regimes.

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Sea-ice lead climatology for the Antarctic based on MODIS satellite data

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Sea-ice leads are characterized by open water and thin ice causing large energy and moisture fluxes between ocean and atmosphere. Furthermore, they contribute to the ice production and provide a habitat for animals. In the present study, thermal satellite data from the Moderate Resolution Imaging Spectroradiometer (MODIS) are used to derive Sea-ice lead climatology for the Antarctic for the winter periods 2003–2018 (April–September). This study presents the first high-resolution climatology of sea ice leads for the Southern Ocean. The long-term average lead frequency distribution suggests a strong relationship between leads, bathymetry, and associated tides and currents. These findings are supported by coupled ocean-sea ice model simulations. In particular, pronounced patterns associated to the shelf break and several seabed ridges are detected.

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Re-evaluating the Conventional Definition of the Marginal Ice Zone for the Antarctic

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In polar regions, sea ice is a key factor modulating physical and biogeochemical exchanges between the ocean and atmosphere. The marginal ice zone (MIZ) is particularly sensitive to rapid variations in ocean and atmospheric drivers, which poses a challenge for its proper inclusion in climate models. The MIZ is conventionally defined as 15% to 80% sea ice concentration (SIC). Here, we provide direct evidence that challenges this concentration-based definition through a combined analysis of in-situ, satellite, and reanalysis data. SIC observations were made in winter 2017 and 2019 onboard the R/V S.A. Agulhas II to verify satellite and reanalysis SIC estimates in the Atlantic sector. We used the Antarctic Sea Ice Processes and Climate (ASPeCt) protocol complemented by software-based, automatically-acquired SIC to account for the subjective bias inherent in ship-based observations. The Antarctic winter MIZ was dominated by pancake ice with frazil ice located in the interstices between the individual pancakes. These MIZ conditions were observed for 150–200 km while the remote sensing MIZ was less than 90 km. Most observations recorded pancake ice cover of 50% to 90% SIC and total ice cover (pancake and frazil ice) of 100% SIC. Our data indicates that there is a discrepancy between the concentration-based MIZ definition and the observed surface characteristics of the MIZ during its advancing phase. The MIZ appears to cover larger distances than what is predicted from satellite observations. This extended cover may have implications on surface fluxes through ice, impacting the Antarctic MIZ's representation in climate models.

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The dynamics of Southern Ocean and sea ice response to different anthropogenic forcings

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The high latitude Southern Ocean's response to anthropogenic forcing is a complex interplay of wind and radiative changes at the surface, modulated by the ocean's overturning circulation, and by ocean-sea ice feedbacks. The response to greenhouse gasses and stratospheric ozone depletion is expected to be subtly different, which has implications for projected change as their relative importance changes over the coming decades. Therefore, to constrain projections, a mechanistic understanding of how the ocean-sea ice system responds to them individually is essential.
However, isolating the physical mechanism of this response is complicated by the low signal-to-noise ratio of much of the Southern Ocean (i.e. the signal of climate change is small compared to the high internal variability of the system).
To address this issue, we analyse output from single-forcing experiments in the CESM Large Ensemble. We find that the pattern of wind responses to these forcings is quite similar, but the seasonality is different. This has implications for the ocean's response, and suggests that over the historical period greenhouse gasses may have been a more important factor on Southern Ocean circulation change than ozone depletion.

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Recent sea ice and climate variability in East Antarctica

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Antarctica's sea ice cover is an important component in the global climate system. The variability and recent trends in sea ice concentration are, however, not accurately reproduced by models. This is in part because the processes that determine sea ice distribution are not yet well understood, particularly in the East Antarctic region. With the growing recognition that areas of East Antarctica such as Wilkes Land are more vulnerable to climate change than previously assumed, further research into the drivers of sea ice variability is needed to enable accurate projections of how Antarctic sea ice and climate is likely to change in the future. Here we investigate the effects of climate variability on recent sea ice concentration around East Antarctica by examining the HadISST 40-year (1979-2018) satellite sea ice concentration record and ERA5 atmospheric reanalysis data. Preliminary analysis of the Wilkes Land region shows that sea ice variability was linked with the Indian Ocean Dipole (IOD), where negative IOD phases were associated with reduced sea ice concentration in austral spring, and also to sea surface temperatures (SST) in the equatorial Indian Ocean, along with the Southern Annular Mode (SAM). Further analysis will examine the mechanisms by which these links occur, and the extent to which they may affect change in the East Antarctic Ice Sheet. This will allow for a better understanding of the influence of atmospheric variability on the East Antarctic cryosphere, and lead to more accurate modelling of sea ice extent in the Southern Ocean.

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Satellite observation of a large open ocean polynya on the Maud Rise seamount

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Open-ocean polynyas are the regions of open water within the seasonal sea-ice cover, occurs away from the shore. The occurrence of such polynya is known to have consequence on the Antarctic bottom water propertie, atmospheric circulation, Antarctic marine ecosystem, carbon uptake and primary production. Satellite observations show that a large and most prolonged Maud Rise polynya (Lazarev Sea), reappeared on 14 September 2017 for the first time since its frequent appearance during the 1970s. On 14 September 2017, the areal extent of the polynya was ~9.3 × 103 km2 which expanded maximum on 1 December 2017 up to ~298.1 × 103 km2, lasting for 79 days. The formation of the polynya was due to the combined influence of the (i) existence of the geological features such as seamount (leads to local upliftment of thermocline), (ii) upwelling of warm water into the upper ocean from the thermocline (induced by a large cyclonic ocean eddy and negative wind stress curl), and (iii) the large-scale anomalous atmospheric warming. The mechanism of polynya formation in 2016 was similar to that of 2017.

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Evaluation of the crystal structure of Antarctic Sea Ice from the Marginal Ice Zone from winter and spring 2019

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The South Atlantic Marginal Ice Zone (MIZ) is a region of the Southern Ocean that has historically been under-researched with its sea ice being inaccessible during the winter and spring months. Sea ice crystal structure and stratigraphy has been widely researched and is well-understood across many regions and ice types. However, studies have not shown how sea ice crystal stratigraphy may differ with seasons in a region, as well as how weather and climate systems definitively may affect it. Additionally, pancake sea ice and its stratigraphy has not been reported due to the difficulty of in-situ testing of the structures. The research to be presented aims to describe the difference in Antarctic sea ice in the South Atlantic MIZ collected in the winter and spring of 2019 at different locations. This includes describing the crystal stratigraphy of pancake ice, consolidated ice and brash ice, which will be carried out using cross-polarisation techniques. Additionally, it is hypothesised that the intensity of passing low pressure systems affect the resulting crystal stratigraphy of the sea ice in the region, by inducing a deformation process that can lead to granular ice found at unusual depths in the sea ice.

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Southern Ocean circulation and Antarctic sea ice in a global coupled ocean-sea ice model at three resolutions

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ACCESS-OM2 is a suite of three global coupled ocean - sea ice model configurations at 1, 0.25 and 0.1-degree horizontal resolution, consisting of the MOM5 ocean model coupled to the CICE5 sea-ice model and driven by a prescribed atmosphere (JRA55-do). We will present a comprehensive assessment of the performance of these configurations relative to available ocean and sea ice observations in the Southern Ocean and Antarctic, highlighting the improvements we obtain at increased horizontal resolution. We will also discuss the ability of these models to represent sea ice trends, including the recent decline in Antarctic sea ice extent.

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Ocean-ice interaction in subpolar Southern Ocean generates internal pycnocline

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The internal pycnocline delineates the interface between the wind-driven circulation in the upper $\sim$1000 metres of the ocean, where most of the global ocean uptake of heat and anthropogenic carbon takes place, and the sluggish abyssal circulation below. While ocean observations robustly show the existence of the internal pycnocline, to date our knowledge about the dynamics leading to the generation of this interface is very limited. Here we show that the internal pycnocline is generated by upper-ocean processes in the subpolar Southern Ocean. The internal pycnocline layer integrates multiple high potential vorticity (PV) sublayers that emerge at the base of the winter mixed layer in different regions of the Southern Ocean. The high-PV layers are produced via ocean-sea ice interaction. As the internal pycnocline layer lies within a density class characterised by zero residual flow, the pycnocline's high-PV signal is inferred to propagate northward from the subpolar Southern Ocean via diffusive processes. This process points towards the crucial role of ocean-sea ice interaction in setting the vertical structure of the ocean.

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Wind-driven Sea-Ice Change intensifies subsurface Ocean Warming near West Antarctic

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Climate change observed around Antarctica in recent decades is characterized by distinctive zonally-asymmetric patterns, most pronounced over West Antarctica. The change is evident throughout the cryosphere, marked by land ice melting, thinning of ice shelves, and sea-ice redistribution around West Antarctica, associated with temperature and circulation anomalies in the atmosphere and ocean. Here we examine the links between these changes using observations and numerical simulations. Results show that atmospheric circulation change drives variations in sea-ice distribution and ocean circulation. Most importantly, sea-ice variability alters the efficiency of the ocean's salt pump, driving sub-surface ocean warming and sub-surface salinity increase around West Antarctica through changes in surface salinity and freshwater fluxes. This sub-surface warming may potentially contribute to West Antarctic land ice melting, with important implications for global sea-level rise.

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The Ocean's role in driving Antarctic sea ice variabilities

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Antarctic sea ice processes strongly interact with the atmosphere and the ocean. The changes occurring in sea ice affect the ocean, which could lead to long-lasting effects that can further impact the sea ice. The annual cycle of sea ice influences the formation of bottom and intermediate water masses, which is relevant in the absorption of carbon and heat into the ocean. Hence the changes in sea ice have an effect on global heat and carbon budgets.
In this study, we look at the impact of ocean-sea ice interactions on sea ice trends and predictability using satellite sea ice data from 1985 to 2016. The analysis confirms previous studies showing that spring sea ice is related to anomalies in subsequent seasons. Furthermore, we identify regions of 'persistence', where anomalies continue throughout the summer and autumn, and 're-emergence', where anomalies disappear in summer but re-emerge in autumn. Almost all regions have re-emergence, which is stronger in Ross and Weddell seas. Analysis conducted using the ocean-sea ice model (ACCESS-OM2) also produce persistent and re-emergent patterns. To better understand the physical processes driving these re-emergence and persistence patterns, we will analyse a high-resolution ocean-sea ice model.

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SIPN-South: Coordination of sea-ice predictions for the Southern Ocean

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The Sea Ice Prediction Network's endeavours are expanded to the Southern Ocean by the SIPN-South project. We provide a focal point for seasonal Antarctic sea-ice predictions to the community and offer a platform for interested parties to openly discuss methods and results and assess model performance against observations based on passive microwave remote sensing data. We have completed two exercises to forecast summer sea-ice conditions during the Year Of Polar Prediction and are continuing on with a third season in 2019/20. It is envisaged that the project will continue and expand.

In this paper, we will present results from the three already completed austral summer sea-ice predictions and discuss the outcomes, including comparison against satellite data. While we acknowledge that the models that participated in the exercises so far are not yet employed for operational predictions, it is our goal to facilitate discussions and potentially inform decision processes when forecasting summer sea-ice conditions in the Southern Ocean.

1561

Antarctic Sea Ice variability in connection to local and remote forcing

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In-spite of global warming, the Southern Hemisphere (SH) is the only cryospheric domain that portrays a positive long-term trend in sea ice extent (SIE, 2.61±2.34%/decade) and seasonal (summer 1±0.94%/decade, autumn 3.53±0.31%/decade, winter 1.04±0.46%/decade and spring 0.94±0.46%/decade), over the 1979-2018. The Ross Sea (2.11±1.32%/decade), Indian Ocean (1.25±1.40%/decade) and Pacific Ocean (1.89±1.57%/decade) also had positive trends, while the Bellingshausen & Amundsen Seas (-2.43± 1.91%/decade) exhibits negative trends, and the Weddell Sea (0.81±1.11 %/decade) experience a mixture of positive and negative trends. Since 2014, the sea ice extent has exhibited a dip (-4.2±3.4%/year). Local forcing factors like winds, sea surface (SST) and air temperature (Ta), and turbulent heat flux (TF) and teleconnections like Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), and Southern Annual Mode (SAM) were examined over each decade (1979-1988, 1989-1998,1999-2008, 2009-2018) using Pearson correlation for each of the five sectors. For entire SH, SST, Ta, AMO were highly correlated to SIE during 2009-2018, compared to earlier decades. For Weddell Sea and Indian Oceans, SST and Ta was highly correlated to SIE, while for Pacific Ocean sector only Ta is high correlated, for all decades. SST and Ta were found to be high correlated with SIE for Bellingshausen & Amundsen Sea for all decades. For the Ross Sea SST & Ta are negatively correlated to SIE during 2009-2018. PDO was negatively correlated to SIE during 1979-1988 which switched sign during 1989-2008 for Weddell Sea. The role of local forcing dominates SIE in the last decade.

1516

Understanding the Relationships between Sea Ice Extent Variations and Surface Winds at Multiple Temporal and Spatial scales

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This presentation describes progress towards understanding how winds influence sea ice and whether the relationship between sea ice and winds vary at different temporal and spatial scales. The aim of this work is to quantify the sensitivity of sea ice concentrations to surface winds and whether there are thresholds associated with the wind speeds or other factors which must be passed for different sea ice regions to respond to these winds. The relationships to high and low frequency variations are also examined specifically and the underlying physical processes which explain these responses. To analyse these processes, we examine the Bootstrap sea ice concentration (SIC) satellite data set derived from SSM/I brightness temperatures and how they are connected to surface winds from the ERA5 reanalysis over the period 1979 to 2018. While analysis is completed over the entire sea ice zone around Antarctica, special attention is paid to the Ross Sea region and the Ross Sea Polynya. In particular, a range of machine learning schemes are tested to determine whether they can be used to identify spatial regions in which sea ice responds to winds coherently.

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Antarctic sea ice budgets in ACCESS-CM2 model compared to other CMIP6 models.

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The ACCESS-CM2 model has a realistic Southern Hemisphere sea ice extent and area in winter in the historical and pre-industrial control simulations but too little ice in summer. The model's ice thickness is too thin compared to the limited shipboard observations that exist in the ASPeCt data set. We have compared these results with the sea ice results in ACCESS ESM1-5 which were similar to the results from the CMIP5 model ACCESS1-3. All three models have a warm bias in the Southern Ocean sea surface temperature (a common feature in many climate models) which contributes to the summer ice extent bias seen in ACCESS-CM2.
For SIMIP, a project of CMIP6, additional diagnostics have been saved that allow us to investigate the sea ice budget: components that lead to ice growth (frazil, basal, snow ice), melt processes (top, basal, lateral), loss due to sublimation and ice advection. There has already been an inter-comparison study on these SIMIP budget terms on the Arctic region. Here we undertake one for the Antarctic and for key regional sectors of the Antarctic, where the response is due to different atmospheric and oceanic drivers.
We compare ACCESS-CM2 results with selected CMIP6 models that also have a full set of data of the required budget terms, available through the Earth Systems Grid, and that produce a realistic winter sea ice maximum extent and some summer sea ice coverage.

1519

Sea ice state along the Victoria Land Coast, Western Ross Sea, characterized by airborne and satellite measurements in spring 2017

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Direct assessment of the sea ice mass balance requires information about ice thickness, which is a major uncertainty in Antarctic sea ice studies. We aim to establish a relationship between satellite derived trends in sea ice cover and region-wide ice thickness distribution. In 2017 we conducted airborne measurements over pack ice, partly along CryoSat-2 satellite altimeter tracks, to assess sea ice morphology between Ross Island and Cape Adare. Our objective is to shed light on geophysical processes which allow to better explain the complex sea ice structure in this important region of net sea ice production. As our main instrument we used an airborne electromagnetic induction sounder, which is deployed from a DC-3 aircraft simultaneously with a lidar and camera.

We present the results of our survey flights in combination with a satellite data assessment to characterize the sea ice morphology in the area. For our statistical analysis of the pack ice conditions we take into account the sea ice drift pattern during the airborne observations. Strong ice thickness gradients have been observed from the polynya regions towards the central Ross Sea as a result of thermodynamic growth. Ice is then heavily deformed in export regions of the McMurdo Sound and Ross Sea polynya where it converges with ice originating from Terra Nova Bay. Variations in modal thickness are identified as various stages of deformed ice. An improved picture of the formation history and current state of the sea ice the Western Ross Sea is drawn.

733

The Annual Cycle of Antarctic sea ice extent: the influence of the Semi-Annual Oscillation on phase.

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The annual cycle of Antarctic sea ice extent is asymmetric. On average, total Antarctic sea ice extent expands (advances) for approximately seven and a half months, from late February to late September, and contracts (retreats) for four and a half months each year. While other factors may influence the size of the extent, previous research suggests that the timing of the growth and retreat stages, also called the phase, is in part due to the influence of the semi-annual oscillation (SAO) of the Antarctic circumpolar trough (Enomoto and Ohmura, 1990; Watkins and Simmonds, 1999). Using observed daily sea ice extent, we create and evaluate a timeseries of the phase of Antarctic sea ice over the period 1979-2018. Using sea ice concentration, sea level pressure, and winds, over the same period, we compare the strength and timing of the observed SAO and the related winds with the variability of the observed phase of the annual cycle and the breakup of ice within the pack. The results are used to help understand the anomalously rapid sea ice decay which occurred in 2016.

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What we can learn from a year of sea ice

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Antarctic sea ice is an integrator of ocean, atmosphere and cryosphere climate elements and reveals facets of these climate systems and their interactions that are otherwise difficult to observe. Here we examine these interactions with a focus on the regional and seasonal variability of sea-ice cover and associated drivers. We use and expand on the analysis from the most recent Bulletin of the American Meteorological Society's State of the Climate Antarctic sea ice report for the year 2019, while briefly putting this into historical perspective. We cover the large-scale drivers of sea ice, setting the regional variability into context with long-term trends. Factors considered include tropical drivers (high-low latitude interaction), cross-cryosphere interactions, and sea-ice momentum. We also touch on the influence of transient cyclones on the position of the sea ice edge.

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Upper ocean properties around the South Orkney Islands, Antarctica, in two years of contrasting sea ice conditions

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The South Orkney Islands and the surrounding plateau, situated in the Weddell Scotia Confluence between the Antarctic Circumpolar Current and the Weddell Front, are a highly productive and important region for the ecosystem in the Atlantic sector of the Southern Ocean. A hotspot for Antarctic krill, the region is a key fishing ground for the commercial krill fishery. Processes influencing the advection and retention of krill around the South Orkneys have impacts not only locally, but across a wider region downstream. The circulation around the South Orkney Plateau is dominated by a topographically steered boundary current which transports surface and intermediate water masses along the shelf break. In this study, we present observations from two hydrographic surveys across the plateau in 2016 and 2019. These two years were characterized by opposing patterns in the sea ice coverage prior to the surveys, and the large-scale climate state linked to El Niño. We analyse water mass properties and transformations along the pathway of the boundary current and explore linkages to sea ice and the atmosphere through freshwater input from ice melt and sea surface temperature anomalies. Particular focus is on the northern edge of the plateau and a canyon situated on the northwest of the plateau, in which large krill aggregations frequently occur.

244

Where is it and what is it doing?

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A precise knowledge of the thickness of sea ice is important for: estimating sea ice volume; determining mechanical strength; understanding light penetration; and monitoring the sea ice growth and decay. However, defining the underside of the ice is not straightforward, for example in McMurdo Sound, Antarctica when a sub-ice platelet layer is present. The friable sub-ice platelet layer consists of ice platelets of seemingly random orientation under the consolidated sea ice. Thermistor strings are commonly used to observe sea ice thickness over long time periods and different methods of processing thermistor data are found in the literature. So far, there is very limited understanding of the uncertainties associated with estimating sea ice thickness from thermistor strings. This makes it difficult to quantify natural variability and assess whether changes are part of a long-term trend. We present an analysis of sea ice thicknesses calculated from thermistor strings deployed in McMurdo Sound over two decades. We compare different methods of processing the data to determine the ice-ocean interface and investigate the robustness, precision and accuracy of these methods. The results are compared to other acoustic/mechanical methods and locations. The resulting 20 year thickness time-series provides the rare opportunity to quantify interannual variability and study existing or emerging trends in McMurdo Sound sea ice whilst talking into account the uncertainties introduced by the methods. The aim is to make it easier to analyse and compare observations, and assist in constraining the range of variability and the rate of change in sea ice thickness.

1698

Investigating ocean and atmosphere anomalies on and off the Ross Sea continental shelf to help explain persistent low sea ice in the Ross Sea since spring 2016

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Several mechanisms have been previously proposed to explain the record-breaking low sea ice extent in the Ross Sea in spring 2016, including the high latitude response to tropical forcing, combined with internal & regional atmospheric variability (e.g., zonal wave 3, SAM), as well as persistent ocean thermal anomalies operating at seasonal to decadal time scales. This record low spring sea ice extent in the Ross Sea was particularly noteworthy since it stood in stark contrast to the strong positive sea ice extent trends previously observed in all seasons in the Ross Sea (though strongest in autumn and spring).

Remarkably, since spring 2016, the Ross Sea continues to experience anomalously low sea ice extent. Here we explore autumn-winter ocean data acquired during PIPERS (Polynyas, Ice Production and seasonal Evolution in the Ross Sea) in 2017 to explore both ocean (e.g., anomalous surface/sub-surface ocean heat and water mass distribution) and atmospheric (e.g., anomalous wind/wave and surface solar heating) processes that may have contributed to the anomalously late autumn-winter ice edge advance and thickness evolution in 2017. We also highlight potentially different mechanisms that may be operating on and off the continental shelf as well as seasonally. Finally, the 2017 ocean and atmospheric conditions are compared to available historic data to explore potential explanations for the multi-year persistence of low sea ice in the Ross Sea since spring 2016.

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Sea ice and tidal rectification drive the Antarctic Slope Front

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The Antarctic Slope Front (ASF) separates the cold waters of the Antarctic continental shelf from the warmer waters of the Southern Ocean. Previous studies have explained the ASF as a result of wind-driven Ekman transport toward the coast, but have largely overlooked two key drivers of the circulation: (i) sea ice, which mediates momentum input to the ocean, and (ii) acceleration of the along-slope flow by tidal motions.

In this presentation we first investigate the momentum balance and overturning circulation of the ASF using a high-resolution (1/48th degree) global ECCO2 ocean/sea ice simulation. Over the continental slope, we show that surface stresses associated with sea ice drift accelerate the ocean flow westward, and the resulting Ekman overturning circulation serves to steepen the ASF. In contrast, over the continental shelf break we find that tides accelerate the flow to a similar speed as the overlying sea ice, such that the surface stress approximately vanishes. Consequently tides, rather than surface stresses, drive the overturning circulation that steepens the ASF at the shelf break.

To elucidate this interplay between tides and sea ice in the ASF, we conduct process-oriented high-resolution simulations with varying sea ice thicknesses, tidal amplitudes, and cross-slope buoyancy gradients. We find that ice-ocean drag and tidal rectification primarily control the barotropic component of the along-slope flow, while cross-slope buoyancy gradients primarily set the baroclinic structure of the ASF. These findings therefore revise current understanding of the processes that set the ASF's density structure, ocean transport and sea ice drift.

1714

The role of Antarctica sea ice on modulating the Primary Productivity in the Southern Ocean

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Chlorophyll concentration (Chl-a) is a primary proxy for primary productivity in the oceans. Various physical and biogeochemical parameters are known to govern Chl-a. In the Southern Ocean, sea ice is known to be one of the major factors affecting the regional temperature of the ocean and hence its primary productivity. Hence, analyzing the variations in regional sea ice extent in this region would assist in understanding the Chl-a, and hence primary productivity. Further, sea ice is also quite sensitive to the effects of climate change. The sea ice extent and corresponding Chl-a variability in the Southern Ocean have been studied in this work utilizing more than 35 years remotely sensed sea ice data and about 15 years of Chl-a and Sea Surface Temperature observations. It was found that the offshore katabatic winds blowing from the Antarctic coast enhances the sea ice extent during winter, while diminishing the sea ice melting in the summer. The Weddell region shows the highest sea ice extent of 3×106 km2 during summer, where as other regions show a sea ice extent of less than 1.9×106 km2, where the wind blows alongshore or towards the coast. The vertical structure of various bio-physical parameters in the Southern Ocean as available from few Bio-Argo floats in the study region were also examined which revealed the nutricline in the region to directly affect the Chl-a distribution.

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Reconsideration of snow effect on growth and preservation for Antarctic multi-year landfast sea ice

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Long-lived perennial sea ice, or multi-year ice (MYI), has been formed near the front of ice sheet and glaciers. Landfast MYI has a buttress role for glaciers and a factor affecting variability of ocean-glacier subsystem. Satellite observations suggest that MYI has existed for over 30 years in Lützow-Holm Bay near 39E in East Antarctica. Under heavy snow condition, sea ice is supposed to be upward thicker through formations of snow ice and/or superimposed ice. Even in much snow, sea ice has not grown indefinitely, according to an airborne-EM measurement data. MYI existence contributes to landfast ice stability. Stable or unstable regimes for landfast ice in the bay have been alternately repeated since 1980 with several to ten years interval. Interannual variability of snow accumulation as well as events of ice breakup have been examined together the analysis of ice core. Note that snowpack gives opposite effects on preservation of ice; one is mechanically reinforcement by thickening through upward-growth and high albedo; the other is weakening due to lowering flexural strength by increasing the ratio of snow-origin ice. There is no doubt that the snowpack has affected strongly physical modification of ice body. A growth history of sea ice is reflected in physical and biogeochemical characteristics, such as ice texture, salinity, and stable isotopic structures of the core sample. An ice sample has been collected with 3.86 m in length near the Shirase Glacier in 2018/19 season. We report the in-situ drilling operation and show features of sea-ice structures.

1267

Air-sea-ice interactions at the mesoscale : case study of the Mertz Glacier Polynya in a regional climate model.

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The Mertz Glacier Polynya, in east Antarctica, is a limited area of the Southern Ocean, which is often free ice even during the austral winter. The absence of sea ice in the polynya allows for intense exchanges of heat, moisture, and momentum between the cold and dry atmosphere and the relatively warmer ocean. Despite being paramount features of the polar climate, little is known about the processes taking place between the ocean, ice and atmosphere in polynyas. Here, we describe the dynamics of the Mertz Glacier Polynya using a high resolution regional coupled model of the ocean, sea ice and atmosphere (NEMO-LIM 3.6 and MAR). We describe the daily to seasonal variability of the polynya activity and air-sea fluxes during years 2012-2013. We then assess the impacts of the polynya on the formation of Dense Shelf Water and basal melt of neighboring ice shelves. We also analyze the response of the atmosphere to the presence and variability of ice free area. To assess the effect of potential feedbacks, we conduct a second set of experiments in standalone forced mode. Finally, we perform an experiment using the coastline prior to the Mertz calving in 2010, to test the sensitivity of air-sea-ice interactions to drastic changes in polynya activity. This work improves the understanding of the exchanges taking place in polynya together with their impact on regional polar climate. It also represents a further step in the representation of polar regions in climate models.

1064

Using historical whale catch data to evaluate climate model results in the Southern Ocean

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The assessment of historical climate model simulations in the Southern Ocean is limited by the availability of oceanographic records during the 20th century until remote sensing observations. Whale catch data can help to fill this gap, because they represent a wealth of information on the habitat distribution of commercial whales and the underlying environmental conditions. Although the impact of commercial whaling makes difficult to disentangle the drivers of the spatial and temporal distributions, these data have been used in the past as proxy for the location of major ocean features, such as the sea-ice edge. We propose here a use of these data to assess various macroscopic features of climate model results from the suite of the Climate Model Intercomparison Project phase 6 (CMIP6) during the historical simulation period (1920-1970). We have focused on humpback whales, due to their particular environmental niche and for being the species targeted the most at the beginning of the century. This species is usually found in open waters adjacent to the sea ice edge, and can therefore provide an optimal proxy for oceanic conditions. The results using 22 CMIP6 models indicate that the model median overestimate the extent of summer Antarctic sea ice. In the majority of models, the historical sea-ice edge is simulated northward of the typical regions in which humpback whales were caught. This is an indication that the tuning and assessment of sea ice models using satellite-era observations may lead to an overshooting of Antarctic ice extent earlier in the century.

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